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CALCULATING PAYLOAD FOR A TETHERED BALLOON SYSTEM

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ABSTRACT.—A graph method to calculate payload for a tethered balloon system, with the supporting helium lift and payload equations, is described. The balloon system is designed to collect emissions data during the convective-lift and no-convective-lift phases of a forest fire. A description of the balloon system and a list of factors affecting balloon selection are included.

Keywords: Smoke plumes, forest fires, particulate matter, emission rate, helium lift, balloon payload, air pollution measurement.

The Southern Forest Fire Laboratory (SFFL) has developed a tethered balloon system for profiling smoke plumes from forest fires (Ryan and others 1979). The profiling method, developed by Ward and others (1974), was designed to collect emissions of total suspended particulate matter (TSP) from low-intensity prescribed fires backing against the wind. Towers 12.2 m high were used to support filters to collect particulates, which limits this method to short periods when winds are steady and the angle of plume rise is low enough so that the rising smoke is below the tops of the towers. The tethered balloon system extends this direct-measuring filter system to fires of higher intensity and longer burning periods.

Several groups have used aircraft to sample higher intensity and longer burning fires (Radke and others 1978; Packham and Vines 1978; Ward and others 1979). The behavior of these fires limits this method to sampling only the emissions associated with a well-developed plume produced during the convective-lift (CL) phase of a fire. During the no-convective-lift (NCL) phase of the fire, emissions are too close to the ground to accommodate aircraft sampling. In addition to this limitation, aircraft sampling does not always acquire fuel consumption data, it depends on indirect methods of measuring TSP (e.g., nephelometer, particle spectrometer), can have navigational problems, and cannot safely be used at low altitudes in rough terrain.

The SFFL tethered balloon system surmounts the limitations of tower and aircraft systems. It is designed to collect emissions data from both well-defined smoke plumes up to 600 m above ground level (AGL) during the CL phase of a fire and from smoke drifting near the ground during the NCL phase at sites ranging from sea level to 2,400 m above mean sea level (MSL). Thus, it gives us the ability to measure emissions over the entire course of the fire. Also, being a ground-based system, it is not subject to the navigational problems of an aircraft system, and is in a better position to collect fuel consumption data.

Essential to a balloon system is the development of a method to determine the balloon's static lift and payload to determine the amount of sampling equipment that can be suspended from the balloon. The purpose of this paper is to describe the development of the helium lift equations and present a simplified method to calculate the static lift of the SFFL balloon system and the number of smoke plume sampling packages (payload) that can be lifted by this system. Field studies with a balloon system should begin with a review of this information.

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STATIC LIFT

Helium Lift Coefficient

The static lift of a balloon is determined from

Archimedes' principle, but for balloon lift analysis the displaced fluid is air and the immersed body is the helium-filled balloon. The effect of the buoyant force of the air is to give lift to the balloon, and the amount of this lift is the difference between the weight of the displaced air and that of the helium and balloon. Considering first only the effect of a unit volume of the gases air and helium, this difference can be expressed as (Myers 1968)

$$C_l = w_a - w_h \tag{1}$$

where

C_l = lift coefficient of helium, kg/m^3
w_a = weight of a unit volume of air, kg/m^3
w_h = weight of a unit volume of helium, kg/m^3

The SFFL tethered balloon system was designed principally for use on prescribed fires. The recommended range of air temperatures for these fires is about −4°C to 15°C. In addition, these prescribed fires take place at elevations ranging from sea level to 2,400 m. Two variables—temperature and pressure—are now introduced that affect the weight per unit volume of the air and helium. Humidity also affects the weight of air, but the effect is of little consequence, especially in the range from 30 to 50 percent relative humidity preferred for prescribed burning. Two laws of gas expansion, Charles' or Gay-Lussac's and Boyle's, state the effects that temperature and pressure have on the volume of a gas. Combined, they give the general law for gases

$$P_0V_0/T_0 = PV/T \tag{2}$$

where P_0V_0 and T_0 are the pressure, volume, and absolute temperature for a mass of gas at an initial set of values and P, V, and T the same quantities for the same mass of gas at a final set.

Gas volume has a direct and inverse relation to gas density. Substituting density, ρ, for volume in Equation (2) and solving for ρ gives

$$\rho = (P/P_0)\,(T_0/T)\,\rho_0 \tag{3}$$

If we define the initial set of values as those of a standard atmosphere at MSL and the final set as those of a standard atmosphere at a given elevation, then the variables of Equation (3) are defined as

ρ = air density for a standard atmosphere at a given elevation, kg/m^3
ρ_0 = air density for a standard atmosphere at MSL, kg/m^3
P = atmospheric pressure for a standard atmosphere at a given elevation, mm Hg
P_0 = atmospheric pressure for a standard atmosphere at MSL, mm Hg
T = absolute air temperature for a standard atmosphere at a given elevation, K
T_0 = absolute air temperature for a standard atmosphere at MSL, K

Values of ρ have been calculated and tables for the U.S. standard atmosphere produced for a range of elevations (Bolz and Tuve 1973). The ratio ρ/ρ_0, taken from this table, gives the fractional value of air density at a given elevation. This fractional value is the same for any gas and, therefore, the difference between gases. Since w_a and w_h in Equation (1) are actually densities, the ratio ρ/ρ_0 can be applied to their difference. Assuming initial values of a standard atmosphere at MSL, this gives

$$C_{l_s} = (\rho/\rho_0)\,C_{l_0} \tag{4}$$

where

C_{l_s} = lift coefficient of helium for a standard atmosphere at a given elevation, kg/m^3.
C_{l_0} = lift coefficient of helium for a standard atmosphere at MSL, kg/m^3.

A standard atmosphere does not frequently prevail, so we must go beyond Equation (4). Air temperature is often much different from standard. To account for this, we go back to Charles' or Gay-Lussac's law of the expansion of gases and apply this to a volume of air at a given elevation

$$V/V_a = T/T_a \tag{5}$$

Substituting density for volume and solving for ρ_a gives

$$\rho_a = (T/T_a)\rho \tag{6}$$

where

ρ_a = air density at a given elevation, kg/m^3

T_a = absolute air temperature at a given elevation, K.

Although Equation (6) is defined for air density, it applies to the density of any gas and, therefore, to the difference between gases. Substituting the density difference between air and helium, C_l, for ρ_a and the density difference given in Equation (4), C_{l_s} for ρ gives

$$
\begin{aligned}
C_l &= (T/T_a)\, C_{l_s} \\
&= (T/T_a)\,(\rho/\rho_0)\, C_{l_0} \qquad (7)
\end{aligned}
$$

where

C_l = lift coefficient of helium at a given elevation, kg/m^3

One assumption made in the development of Equation (7) is that the temperature and pressure of the helium inside the balloon and that of the ambient air are the same. This assumption introduces some error. The pressure inside the balloon is kept at only a few inches of water higher than ambient to prevent the balloon nose from cupping in high winds and, therefore, contributes little to any error. A greater error is contributed by the increase in helium temperature over air temperature from solar radiation during the day. This difference in temperature is called "superheat." The effect of superheat is explained by Equations (1) and (5) and the construction of the balloon. Increasing the temperature of the helium gas increases its volume. A dilation panel with bungee restraining cord on the underside of the balloon permits the balloon to change volume. This feature maintains the gas pressure inside the balloon during changes in elevation and ambient temperature and also allows the balloon to expand from the effect of superheat. As helium gas is not being added to the balloon, the expanding balloon displaces a greater volume and weight of air with the same weight of helium. As Equation (1) shows, the difference $w_a - w_h$ increases, thus increasing the value of the lift coefficient. If the additional lift provided by superheat is critical to any operation, a method to measure the helium gas temperature should be provided and the information used to modify C_{l_0} in Equation (7). Otherwise the additional lift can be considered as a bonus to ensure a more stable operation. One must remember, however, that if the balloon is operated 24 h per day, the superheat and accompanying additional lift will be lost at night.

The purity of the helium has not been made a part of Equation (7). The high quality of the SFFL balloon construction and envelope material, the nearly 100-percent purity of the delivered gas, and the balloon operating periods of usually less than 1 wk do not require a consideration for purity decay. However, if a balloon is used that does have a definite diffusion of air into and gas out of the balloon, or if the balloon is to remain inflated for several weeks, the helium purity needs to be considered. Common practice is to assume a 95-percent purity for this situation. The purity would be entered as a direct relation to lift in Equation (7).

Balloon Selection

Since Equation (3) gives the lift of a unit volume of helium, it is the basic input to the development of any balloon system. Once the gross static lift of the system has been determined, the size of balloon required is calculated by dividing by C_l. In determining gross static lift and selecting a balloon, a number of factors must be considered:

- Payload.—The weight of the instrument package, or packages, to be lifted by the balloon.
- Balloon shape.—Balloons have been built in Class C, vee, barrage, and natural shapes (Peters and others 1972). The Class C aerodynamic balloon, because of its superior lift-to-drag ratio and thus greater stability, is preferred to the vee and barrage shapes for research experiments.
- Balloon size.— Funding and delivery time determine whether a balloon can be constructed to the operator's specifications or whether a standard model of closest size can be used.
- Envelope material.—Permeability of balloon, along with the length of time it is in operation, determines if there is a need to compensate for gas purity.
- Tethering material.—Look for good strength-to-weight ratio with minimum elongation properties.
- Tethering.—A single tether is usually adequate. If greater control in positioning the balloon is required, a tripod arrangement with three tethers may be needed. This will require more lifting capability for the same payload.
- Temperature range.—The temperature's effect on the lift coefficient must be considered when selecting a balloon size.

• Launch-site elevation.—Elevation also affects the lift coefficient and, therefore, selection of balloon size.

• Balloon's height above ground level.—This factor must be added to launch site for elevation effects. Also, the length of the tether affects lift requirements.

• Flight duration.—An operation of more than 1 day will have diurnal temperature changes and helium losses that affect lift.

The Class C aerodynamic balloon is available as a standard model in sizes ranging from 17 to 99 m^3. We selected the 99-m^3 balloon for the SFFL system, which was adequate for a series of experiments scheduled at a site about 2,400 m above MSL using a variable payload with a maximum weight of 27.6 kg.

Payload

The next step is to develop an equation for gross static lift obtained by combining the balloon volume with the lift coefficient, C_{l_0}, in Equation (7). The lift coefficient in Equation (1) becomes C_{l0} when values of w_a amd w_h for a standard atmosphere at MSL of 15° C air temperature and 760 mm Hg atmospheric pressure are used. For these conditions, w_a is 1.225 kg/m^3 and w_h is 0.169 kg/m^3. Inserting these values into Equation (1) gives C_{l0} = 1.056 kg/m^3. Combining the balloon volume of 99 m^3 with this C_{l0} gives

$$L_g = 104.5\,(T/T_a)\,(\rho/\rho_0) \qquad (8)$$

where

L_g = gross static lift of the balloon, kg.

This is the heaviest load the balloon can lift, but not the load that should be lifted. For a stable flight, especially during strong winds, experience has shown that the gross static lift should exceed the load lifted by 15 percent. Without this extra lift, the balloon will experience large horizontal movements in a figure 8 pattern. Also, if the tether is short (100 m or less) a strong wind can force the balloon to the ground. Modifying Equation (8) to provide a 15-percent allowance for extra lift gives

$$L_n = 91\,(T/T_a)\,(\rho/\rho_0) \qquad (9)$$

where

L_n = net static lift of the balloon, kg.

The SFFL tethered balloon system (fig. 1) is designed to fly the balloon 100 m above the smoke plume from a prescribed forest fire with a vertical array of a maximum of 12 particulate matter and gas sampling packages suspended below the balloon and through the plume. The balloon is controlled by a single tether from a variable-speed winch and a rapid deflation line attached to a wire inside the balloon and secured to the ground. A failure of the tether will put tension on the rapid deflation line and rip open the balloon. Data and sampling-control signals to and from the sampling packages and a ground station are transmitted through an instrumentation line that also supports the packages by attachment to the balloon (fig. 2). Connectors for sampling packages are located at 3-m intervals along the length of the line. The spacing between sampling packages is determined by the height of the plume, and can be arranged in any pattern on the instrumentation line within the limits of a maximum plume height of 600 m AGL and minimum spacing of 3 m.

The load for the SFFL tethered balloon system consists of the tether line, rapid deflation line, instrumentation line, balloon, and sampling packages. The maximum for this load can be expressed in terms of the net static lift

$$L_n = W_l + W_b + W_p \qquad (10)$$

where

W_l = weight of the tether, rapid deflation, and instrumentation lines, kg
W_b = weight of the balloon, kg
W_p = weight of the payload, kg.

This introduces another variable to the calculation of balloon lift, W_l. Because the balloon is flown above the smoke plume, its height AGL depends on the plume's height. The plume's height—determined by the fire's intensity and meteorological conditions—at the balloon's proximity to the fire will vary from a few meters to several hundred meters AGL. As the balloon's height varies, so do the lengths of the tether, rapid deflation, and instrumentation lines, and their weights. Their combined weight per unit length is 0.0485 kg/m.

The payload, W_p, is a set of sampling packages (fig. 3), and the number of packages used with the system at any time depends on the net static lift minus the weights of the lines and balloon. Therefore, before the balloon system can

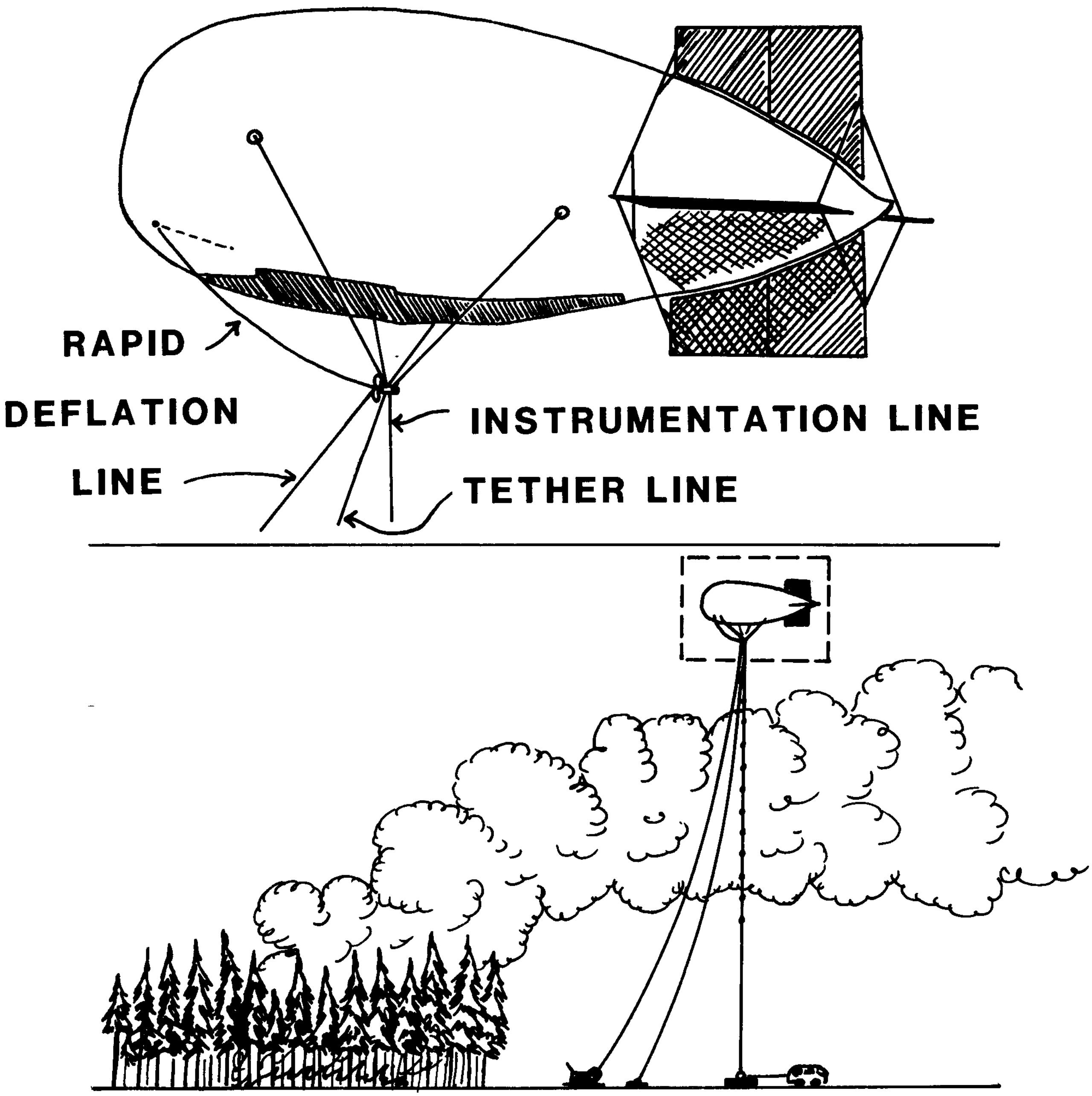

Figure 1.—The SFFL tethered balloon system, suspending sampling packages in the plume from a fire, is controlled by a single tether and rapid deflation line. The upper drawing shows the rapid deflation line tied off at the point where the tether and instrumentation lines are connected to the confluence of the load lines.

Figure 2.—Instrumentation line with sampling packages on "clothesline" support that facilitates sending packages aloft.

be used to sample a plume. Equation (10) must be solved for W_p. Combining Equations (9) and (10) with 43 kg substituted for the weight of the balloon and 0.0485 times the height of the balloon for the combined line weight, and solving for W_p gives

$$W_p = 91\,(T/T_a)\,(\rho/\rho_0) - 0.0485\,h - 43 \qquad (11)$$

where

- W_p = weight of the payload, kg.
- T = absolute air temperature for a standard atmosphere at a given elevation, K.
- T_a = absolute air temperature at a given elevation, K.
- ρ = air density for a standard atmosphere at a given elevation, kg/m³.
- ρ_0 = air density for a standard atmosphere at MSL, kg/m³.
- h = height of the balloon AGL, m.

GRAPH METHOD

Equation (11) is not difficult to compute, but it does require an engineering handbook and a calculator to find values for T and ρ. The handbook and calculator can be left at the office and replaced by a graph developed from Equation (11). The graph is premarked with diagonal lines that indicate a range of balloon elevations and balloon heights, and has scales for air temperature, net static lift, and payload. Figure 4 shows the graph, and figure 5 gives examples of calculating lift and payload for balloons at two different elevations and temperatures.

Net Static Lift and Payload

In the examples (fig. 5), A represents a balloon with height set at 300 m AGL at a site that is 100 m above MSL, thus making balloon elevation 400 m above MSL at an air temperature of 14°C.

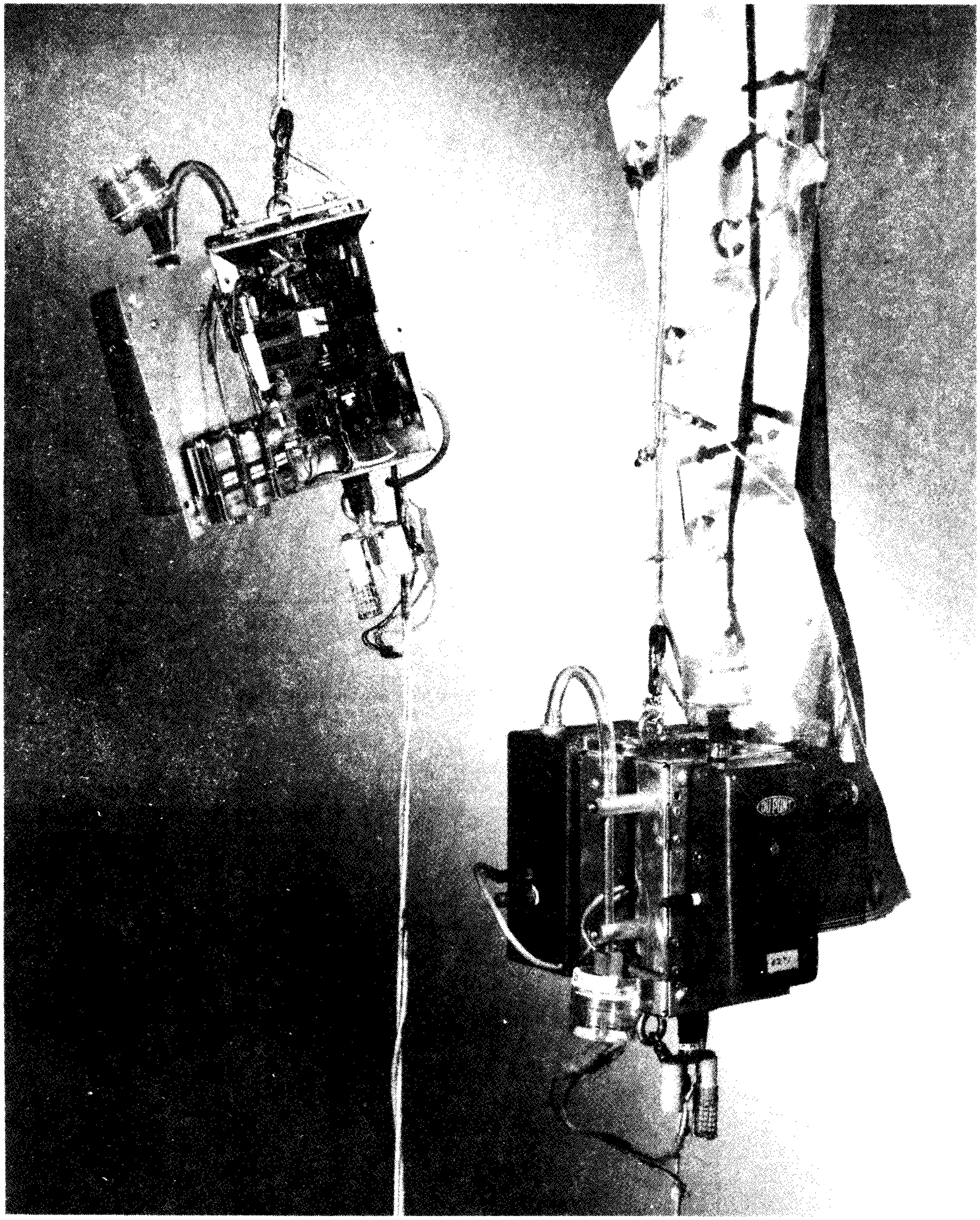

Figure 3.—Sampling packages attached to the instrumentation line: on the left, opened to expose electronics and batteries; on the right, with gas bag attached.

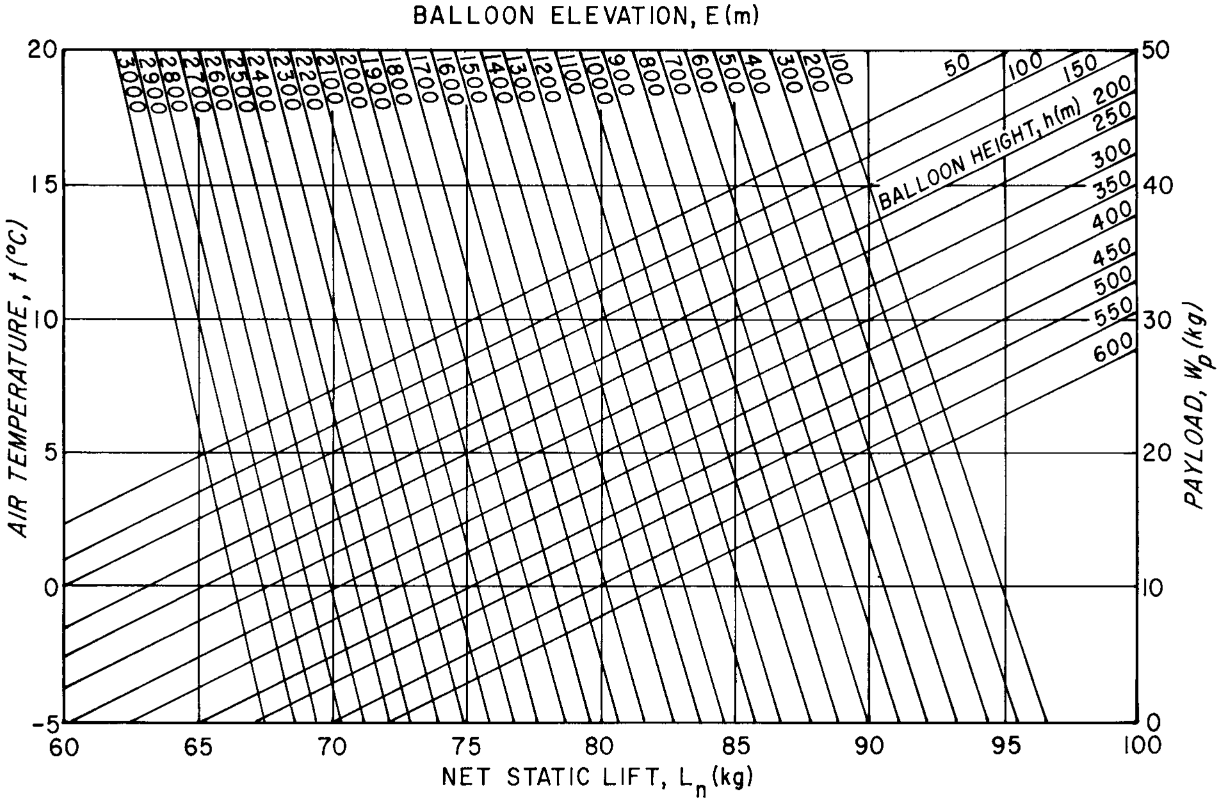

Figure 4.—Graph used to determine net static lift and payload.

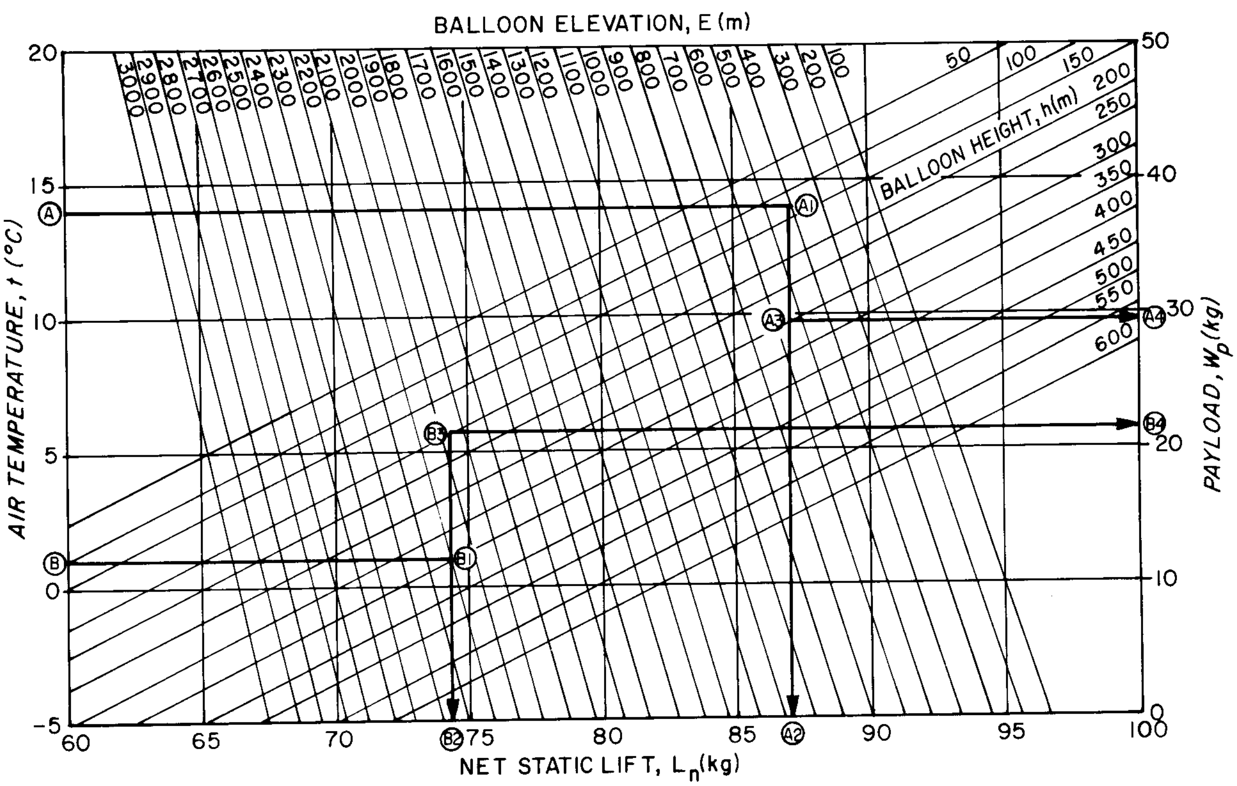

Figure 5.—Net static lift is determined by drawing a horizontal line from the air temperature value (A) at the left-hand side of the graph to its intersect with the diagonal at the balloon's elevation (A1), then drawing a vertical line from that point to its intersect with the bottom line of the graph (A2). Payload is determined at the intersect of this vertical line with the diagonal at the balloon's height (A3) by drawing a horizontal line to the right-hand side of the graph (A4).

Net static lift is determined by the intersect of air temperature at the balloon's elevation. To determine net static lift, begin with the air temperature (left-hand side of the graph) at the balloon's elevation. Draw a horizontal line from the temperature point to its intersect with the diagonal that indicates the balloon's elevation above MSL (400 m). Draw a vertical line from this point to the bottom of the graph that gives the net static lift at that intersect—in this case, 87.1 kg. The intersect of this same vertical line with the diagonal at the balloon's height AGL (300 m) determines the payload. Draw a horizontal line from this point to the right-hand side of the graph that gives the payload at that intersect, which is 29.5 kg for this example.

In the second example, B represents a balloon with height set at 200 m AGL at a site that is 1,900 m above MSL, making the balloon's elevation 2,100 m above MSL at an air temperature of 1°C. Again, determine the net static lift by starting with the air temperature at the balloon's elevation. Draw a horizontal line from this point to its intersect with the diagonal that indicates the balloon's elevation above MSL (2,100 m). From this point, draw a vertical line to the bottom of the graph that gives the net static lift at the intersect, which is 74.2 kg for example B. Extend this vertical line upward to the point on the diagonal line that indicates the balloon's height AGL (200 m) to determine payload. Draw a horizontal line from this point to the right-hand side of the graph which gives payload at that intersect, which is 21.5 kg for this example.

The purpose of Equation (11) and the graph is to determine the number of sampling packages that can be attached to the balloon's instrumentation line for any set of conditions. At present, the system has 12 sampling packages, each weighing 2.3 kg. In the examples, the payload for balloon A of 29.5 kg can accommodate 12 packages, with lift to spare. The payload for balloon B of 21.5 kg limits the number of packages to nine.

Graph Accuracy

In addition to offering speed and simplicity, the graph (fig. 4) must have enough accuracy built into it to give us confidence that the number of sampling packages selected is correct. For the first entry on the graph, temperature data can be entered with an accuracy of ± 0.05°C. Proceeding through the graph, a 100-m separation between elevation lines gives an interpolation accuracy within ± 10 m, a 50-m separation between height lines gives an interpolation accuracy within ± 5 m, and the intersect with the payload scale can be interpreted within ± 0.1 kg. A plot through the graph of the limits of accuracy produces an error of less than ± 0.5 kg of payload. Since this is only about 4 percent of the excess lift needed for a stable balloon flight, an error caused by the graph will not overload the system.

Any error in the graph should be considered in view of the approximation of Equation (11). A day's operation will see a continuous change in temperature and the predicted temperature may be in error by several degrees. This has a direct effect on Equation (11). The amount of superheat from solar radiation will have an effect on the helium lift coefficient, C_{l0}, that is not accounted for. In addition, the method of inflating the balloon allows the volume to be estimated only at the start of an operation. The accumulation of all of these factors overshadows any error in the graph.

Limits and Options of the Balloon System

In addition to determining net static lift and payload for any set of conditions, figure 5 describes the general relationship between the balloon system and its environment. A quick look at the graph shows how lift decreases with either increasing elevation or temperature. Since lift decreases as conditions move to the left and top of the graph, this is where the limits of the system are to be found. If the balloon is required to be at 600 m AGL, the highest elevation possible for the balloon with just one package ranges from 1,520 m at 20°C temperature to 2,260 m at −5°C. However, the system can lift nine packages to 3,000 m at −5°C if the balloon's height AGL is only 50 m. This illustrates the options facing a balloon operator. At the beginning of the project, the operator can choose the balloon size and payload, but after that, only the payload can be changed. The weather can be chosen only by waiting for the day and time when operating conditions are optimum. The elevation may also be selected if the higher elevation projects can be set aside for days of optimum conditions. However, experience will show that schedules do not always allow for time to wait for the best conditions, which leaves the choice restricted to the size of the payload.

SUMMARY

Two laws of gas expansion, Charles' or Gay-Lussac's and Boyle's, applied to helium and air give an equation of the helium lift coefficient, C_l,

as it is affected by changes in air temperature and air density. The right balloon for the tethered balloon system is selected by considering a number of factors. Combining balloon size with the helium lift coefficient gives the gross static lift from which equations for net static lift and payload are developed. The equations are replaced by a graph that eliminates the need for an engineering handbook and calculator when determining payload for sampling packages.

LITERATURE CITED

Bolz, Ray E., and George L. Tuve, eds.
1973. Handbook of tables for applied engineering science. 2d ed. 1,166 p. Chemical Rubber Co. Press, Cleveland, Ohio.

Myers, P. F.
1968. Tethered balloon handbook. Air Force Cambridge Research Laboratories. Final Report, May 1, 1968–December 31, 1968. 220 p. AFCRL-69-0017(1) rev.

Packham, D. R., and R. G. Vines
1978. Properties of bushfire smoke: The reduction in visibility resulting from prescribed fires in forests. J. Air Pollut. Control Assoc. 28(8):790–795

Peters, P. A., H. H. Lysons, and S. Shindo
1972. Coefficients of four balloon shapes at high attack angles. *In* Proceedings, Seventh AFCRL Scientific Balloon Symposium, p. 19–47.

Radke, L. F., J. L. Stith, D. A. Hegg, and P. V. Hobbs
1978. Airborne studies of particles and gases from forest fires. J. Air Pollut. Control Assoc. 28(1):30–34.

Ryan, Paul W., Charles D. Tangren, and Charles K. McMahon
1979. A balloon system for profiling smoke plumes from forest fires. Pap. 79-6.1 presented at the 72nd Annual Meeting of the Air Pollution Control Association, Cincinnati, Ohio, June 1979.

Ward, D. E., F. R. Elliott, C. K. McMahon, and D. D. Wade
1974. Particulate source strength determination for low-intensity prescribed fires. *In* Proceedings, Control Technology of Agriculture and Pollution Specialty Conference. Air Pollut. Control Assoc., Pittsburgh, Pa. p. 39–55.

Ward, D. E., R. M. Nelson, and R. Adams
1979. Particulate matter in forest fire plumes. Pap. 79-6.3 presented at the 72nd Annual Meeting of the Air Pollution Control Association, Cincinnati, Ohio, June 1979.